

ADVANCED COMPOSITE ELEVATOR FOR BOEING 727 AIRCRAFT

22 FEBRUARY 1979

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SEVENTH QUARTERLY TECHNICAL : PROGRESS REPORT
23 NOVEMBER 1978 THROUGH 22 FEBRUARY 1979

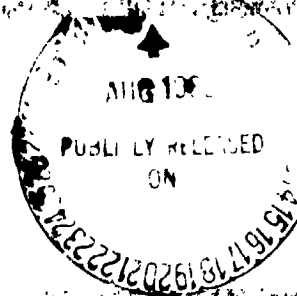
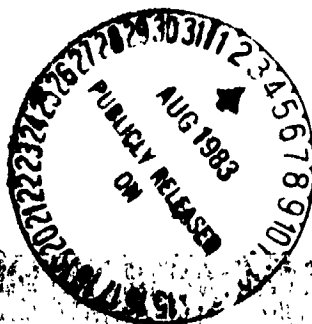
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IN RESPONSE TO:

CONTRACT NAS1-14952
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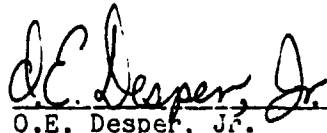
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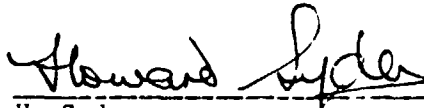
SEVENTH QUARTERLY PROGRESS REPORT
13 November 1978 through 22 February 1979

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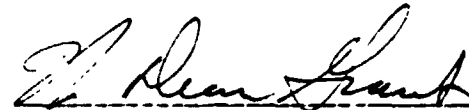
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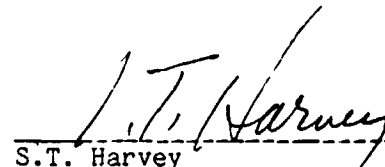
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FOREWORD

This report was prepared by the Boeing Commercial Airplane Company, Renton, Washington, under Contract NAS1-14952. It is the seventh quarterly technical progress report covering work performed between 23 November 1978 and 22 February 1979. The program is sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA-LRC). Dr. H. A. Leybold is the Project Manager for NASA-LRC.

The following Boeing personnel are principal contributors to the program during the reporting period: C. R. Zehnder, Design; R. D. Wilson, Structural Analysis; D. Grant, Production Manager; L. D. Pritchett, Technical Operations Coordinator; and D. B. Chovil, Business Support Manager.

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SUMMARY

Detail design activities are reported for a program to develop an advanced composites elevator for the Boeing 727 commercial transport.

Design activities include discussion of the full-scale ground-test and flight-test activities, the ancillary test programs, sustaining efforts, weight status, and the production status.

Prior to flight testing of the advanced composites elevator, ground, flight-flutter, and stability and control test plans were reviewed and approved by the FAA. Both the ground test and the flight test were conducted according to the approved plan, and were witnessed by the FAA. Three and one-half shipsets have now been fabricated without any significant difficulty being encountered. Two elevator system shipsets were weighed, and results validated the 26% predicted weight reduction. The program is on schedule.

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SECTION 1.0

INTRODUCTION

The escalation of jet-fuel prices is causing a reassessment of technology concepts and trades used in designing and building commercial airplanes. The task is to incorporate fuel-saving concepts into commercial aircraft design.

The potential weight savings and fuel reduction resulting from the extensive use of advanced composites in aircraft structure are significant. However, the lack of technical confidence and cost data has delayed their use in commercial aircraft.

Hardware programs considered in a production environment are required to establish and demonstrate the safety, operating-life characteristics, and manufacturing cost of advanced composites structure.

Boeing's approach to the problem is to obtain reliable production, technical, and cost data bases by the integration of advanced composites technology development under NASA contracts, which, when combined with company effort, will accelerate the application of composites. This approach addresses these data bases, developing realistic production costs in a commercial transport manufacturing environment. Program emphases are directed toward developing the information needed to obtain an early production commitment decision by management, and will be conducted in an environment consistent with production standards.

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Preliminary development efforts, as covered in the first and second quarterly reports, were devoted to conceiving, developing, and analyzing alternative design concepts, and the preparation of a technical plan to aid in selecting and evaluating material, identifying ancillary structural development test requirements, and defining full-scale ground-test and flight-test requirements necessary to obtain FAA certification.

The program was built on precontract design activities as well as contracted design activities that consider:

- Program management and plans development
- Establishing design criteria
- Conceptual and preliminary design
- Manufacturing process development
- Material evaluation and selection
- Verification test
- Detail design
- FAA approval plan definition

This report describes work accomplished during the seventh 3-month period of the contract. Design activities include the discussion of design status, weight status, ground-test and flight-test activities, ancillary-test status, production efforts and costs. These activities are described under the headings: Design Analysis, Ancillary Testing, Ground Test, Flight Test,* and Production. The overall program schedule status is summarized in Figure 1-1.

* The flight-test portion of the program was removed from the NASA contract, and was sponsored by Boeing.

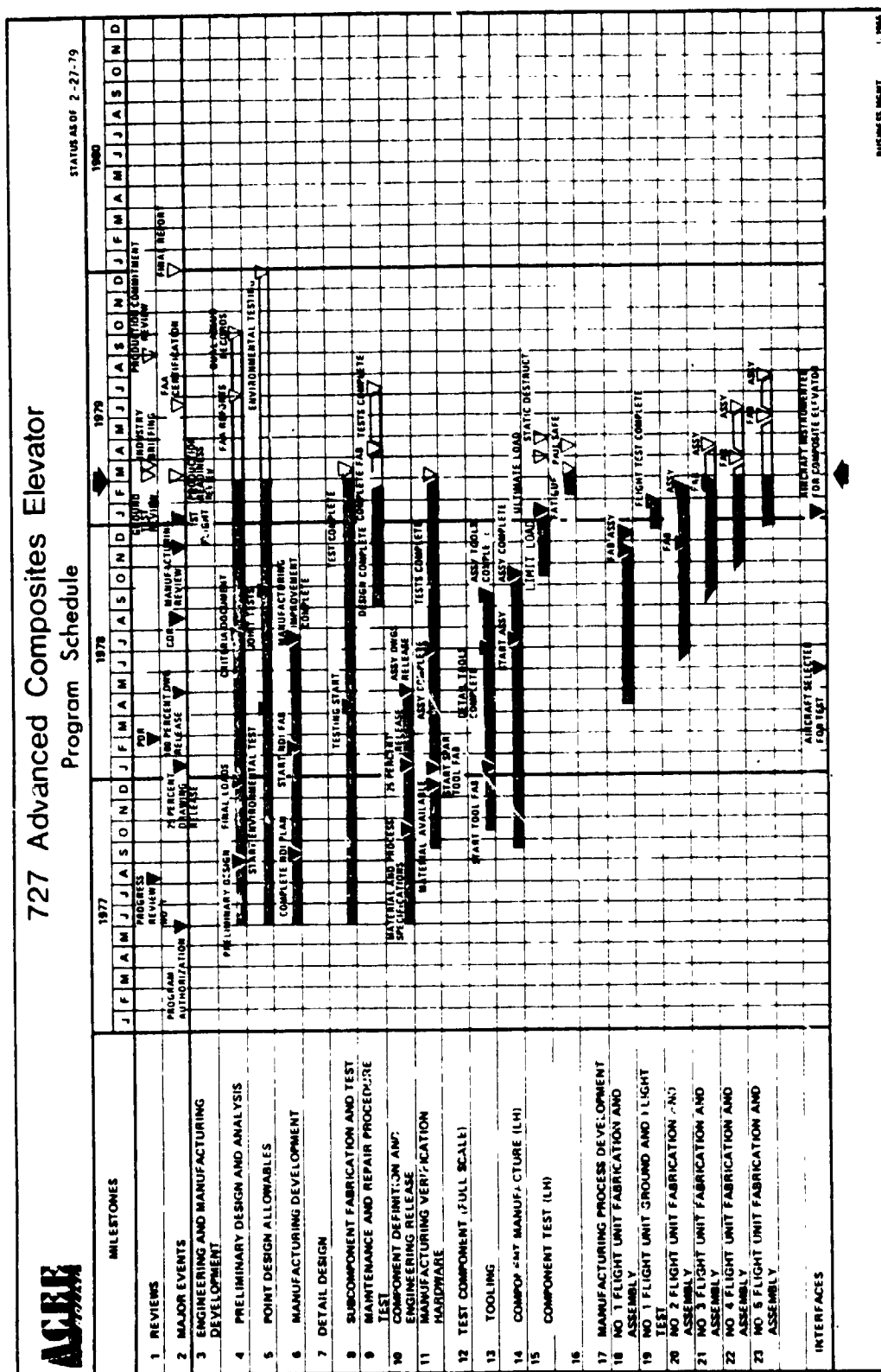


Figure 1-1. Master Program Schedule

SECTION 2.0

DESIGN ANALYSIS

2.1 DESIGN LOADS CRITERIA AND ANALYSIS

Periodic meetings between Boeing and FAA personnel, concerning the 727 elevator structural substantiation plans, have been held throughout the past quarterly period.

Prior to flight testing of the advanced composites elevator, the ground-test plan, flight flutter, and stability and control test plans were reviewed and approved by the FAA. Test plans included testing the full-scale, left-hand ground-test elevator to the critical design limit flight load, prior to on-board participation of the FAA in stability and control flight testing. Ground and flight tests were conducted according to plan, and were witnessed by the FAA.

Meetings between Boeing and FAA personnel were held in January to discuss structural substantiation data to be submitted prior to FAA certification of the 727 advanced composites elevator in June 1979. Items of discussion included materials, material and process specifications, design value derivations, and structural analyses.

2.2 ANCILLARY TESTING--COUPONS AND ELEMENTS

2.2.1 Subcomponent Testing

Honeycomb testing in Test 10 was completed in February. Preliminary load/strain data have been collected for the three most recent

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tests, but are not shown herein. Table 2-1 summarizes the failure loads for all testing associated with this test category. In addition, Table 2-1 references Figure 2-1, which denotes lightning strike location. A discussion of typical failure strain values and failure modes was presented in the fifth quarterly report.

2.2.2 Test 8--Cover Panel Padup at Rib

Testing in this category was completed with the testing of the environmentally conditioned (wet) specimens. On the average, the wet specimens test values are higher than the dry values. See Table 2-2 for a summary of test results. Specimen geometry is shown on drawing 65C17708 in Appendix A of the first quarterly report.

2.2.3 Test 11--Spar Aluminum Splice

A hot/wet (71°C/1.05% moisture content) front spar-to-aluminum actuator support fitting splice was tested on November 30, 1978. The specimen was conditioned in a 100% relative humidity chamber at 60°C for approximately 70 days. The test failure load was 11.1 kN. The failure location is the same as reported for the room temperature, dry test article in the fifth quarterly report in Figures 2-17 through 2-19. The earlier room temperature, dry test article failed at a load of 10.8 kN. The similarity in failure load is consistent with small coupon data, as reported in the sixth quarterly report. The coupon data indicated that, for quasi-isotropic laminates (50% $\pm 45^\circ/0^\circ/90^\circ$ fiber orientation), room temperature, dry and 71°C wet tension test values are essentially equal. Photographs of the hot/wet static test specimen are shown in Figures 2-2 through 2-5.

Table 2-1. Honeycomb Failure Load Summary

	Load at failure, kN	
	Shear	Compression
Room temperature-dry	No. 1 85 No. 2 88 No. 3 86	No. 1 42 No. 2 36 No. 3 35
Room temperature-wet 1	No. 1 56 No. 2 62	No. 1 31 No. 2 31
Room temperature-dry 4 Impacted 2	71	27
Room temperature-dry 4 Lightning damage 3	76	34

- 1 Moisture conditioning was monitored by rider specimens placed alongside the actual test articles in the humidity chamber (see fourth quarterly report, pp. 3-10, 3-11, 3-12)
- 2 Impacted with energy level of 1.13 N-m (10 in-lb) using a spherical-end rod of 19 mm (0.75 in) diameter. Damage consisted of broken fibers and some core crushing. Damage confined to approximately a 12.7 mm (0.5 in) diameter area
- 3 Damage sustained from approximately 50 000A current. Damage confined to a 51 to 76-mm (2 to 3-in) diameter area at locations shown in Figure 2-1
- 4 Failure modes were apparently unaffected by damage; i.e., ultimate failure locations were remote from the damage and similar to undamaged panel failure modes

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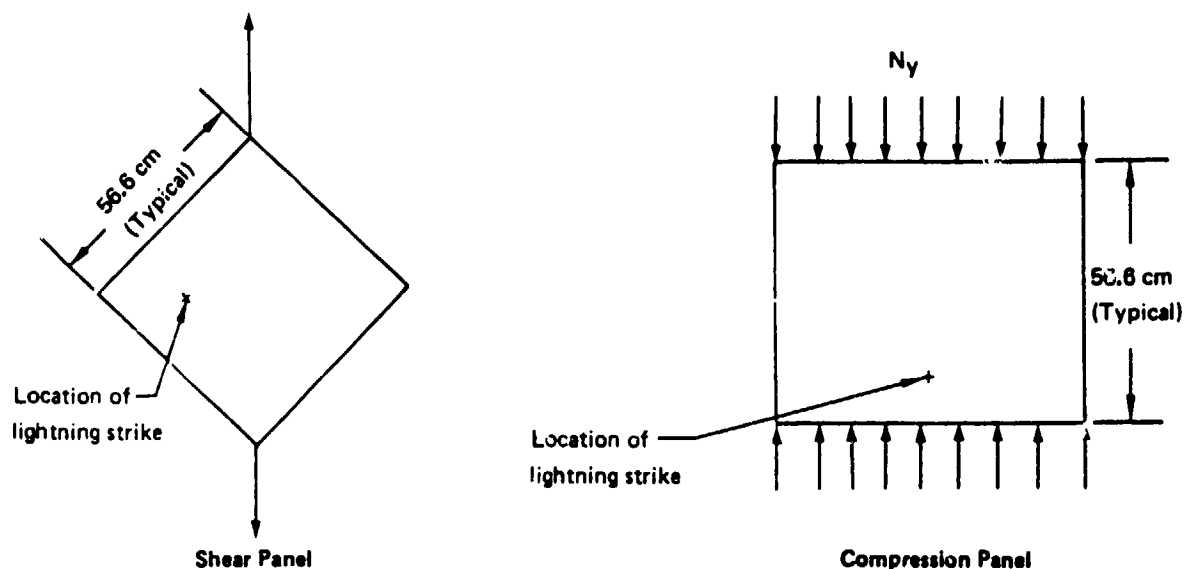


Figure 2-1. Location of Lightning Strikes

Table 2-2. Cover Panel Padup at Rib Test Results Summary

Room temperature static Dry/Wet	Specimen size, cm		Failure load, kN	* Failure stress, MPa
	Width	Skin thickness		
Dry	6.35	0.028	5.226	147.0
Dry	6.35	0.028	5.471	154.2
Dry	6.35	0.028	7.784	219.4
Dry	6.35	0.028	4.136	116.6
Dry	6.35	0.028	6.850	193.1
Dry	6.35	0.028	6.672	187.6
Wet	6.35	0.028	8.273	232.6
Wet	6.35	0.028	7.820	219.9
Wet	6.35	0.028	6.845	192.5

$$* = \frac{\text{Failure load}}{2 \text{ tw}}$$

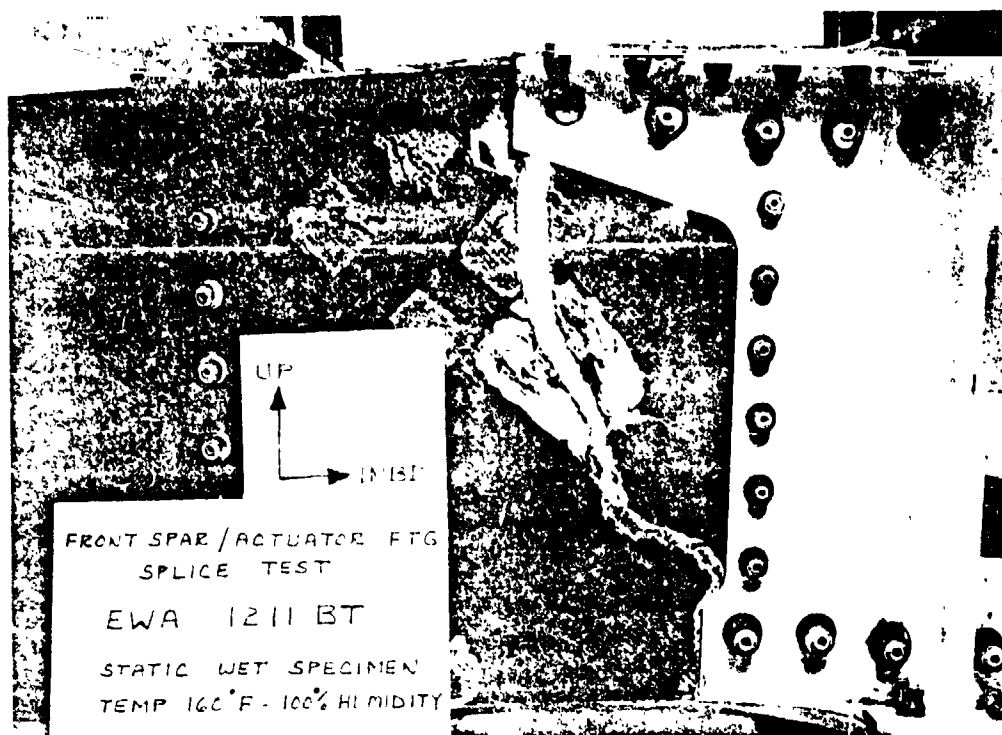


Figure 2-2. Front Spar/Actuator Fitting Splice Test

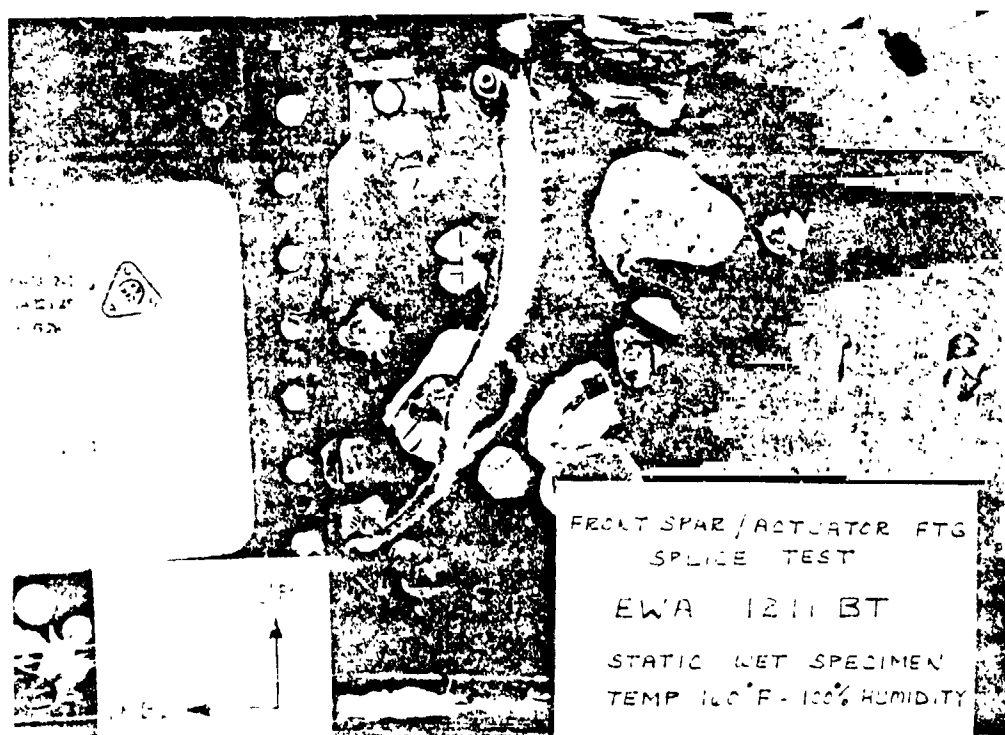


Figure 2-3. Front Spar/Actuator Fitting Splice Test

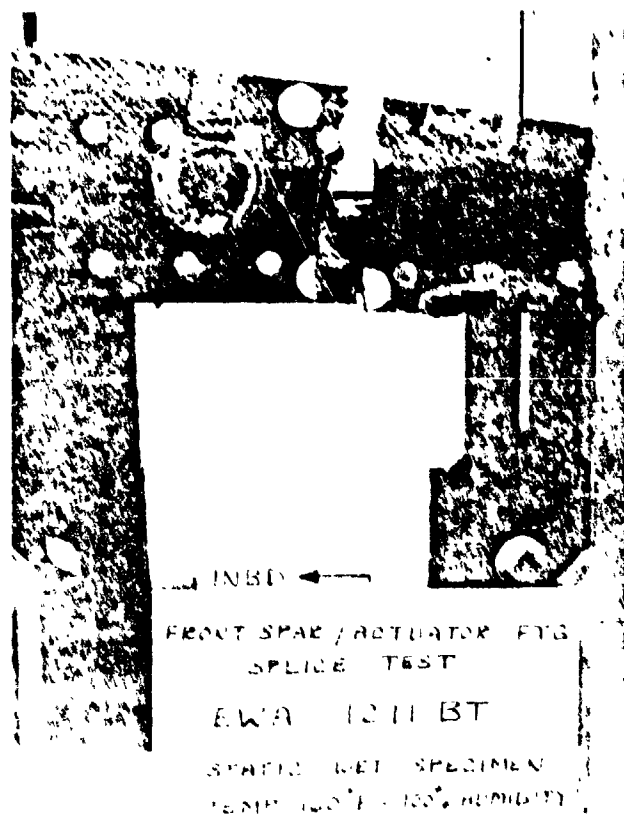


Figure 2-4. Front Spar/Actuator Fitting Splice Test

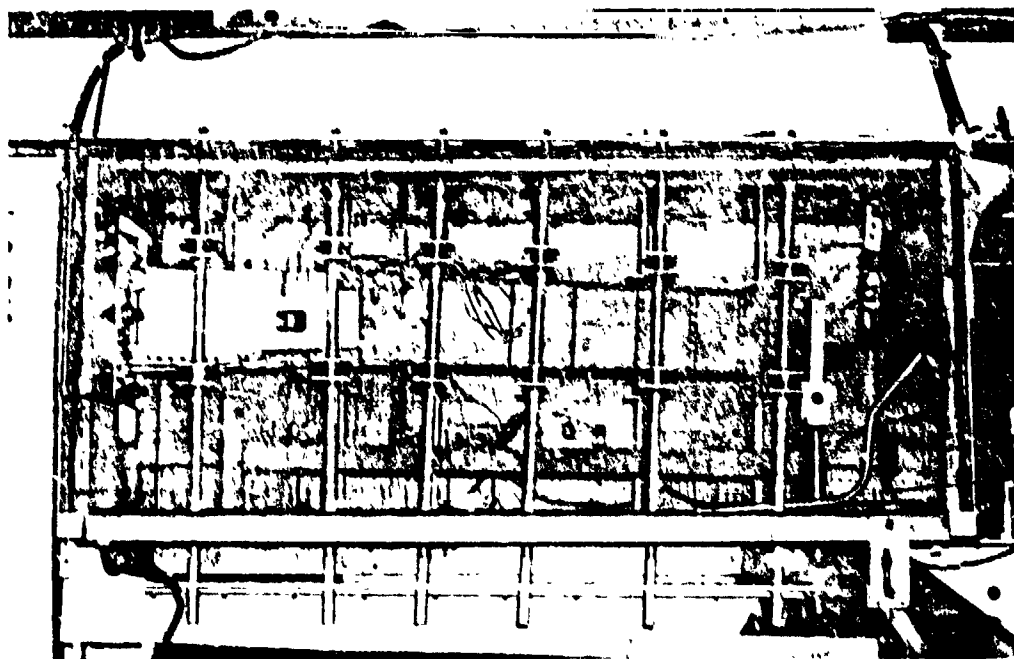


Figure 2-5. Humidity Chamber for Hot Wet Exposure

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The front spar/actuator fitting splice test fatigue specimen has been subjected to a repeated load spectrum test. Blocks of 25 000 load cycles were applied alternately in an environment of 35°C and 100% relative humidity, and then of laboratory ambient temperature and relative humidity.

At the conclusion of one lifetime (of 200 000 cycles), a limit load was applied and deflections were recorded. Cycling was then continued (hot/wet) for another lifetime for a total of 400 000 cycles, and deflection measurements were again recorded. A comparison of deflections taken during the static room temperature, dry tests with those taken at the aforementioned limit loads showed close agreement.

A thorough X-ray inspection of the advanced composites portion of the test specimen at the conclusion of the test did not reveal any fatigue cracks. Inspection of the aluminum actuator fitting also revealed no fatigue cracks.

Further test plans call for some damage testing prior to a destruction test of the specimen.

2.3 FULL-SCALE GROUND TEST

The full-scale ground test elevator has been successfully loaded to limit load, completing the strain survey portion of the test program. Preliminary examination of measured strains, deflections, and hinge and actuator loads generally shows close agreement with those from the finite element ATLAS model values. Figure 2-6 presents a preliminary overview of calculated strains and hinge loads versus measured values. Figures 2-7 through 2-11 are photographs of the test setup and the article under load.

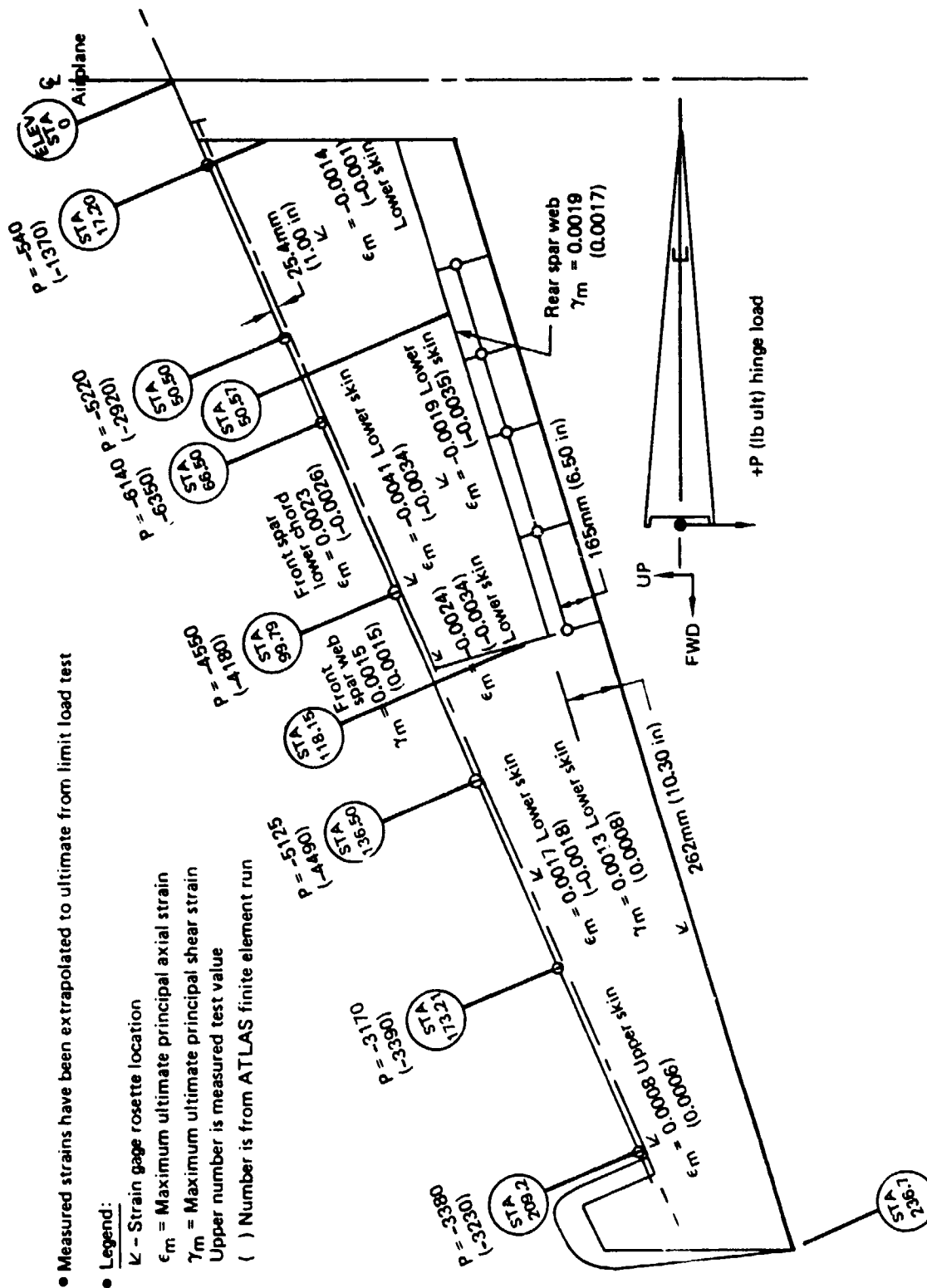


Figure 2-6. Strain Comparisons--Calculated Versus Test

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Figure 2-7. Elevator Ground-Test Setup

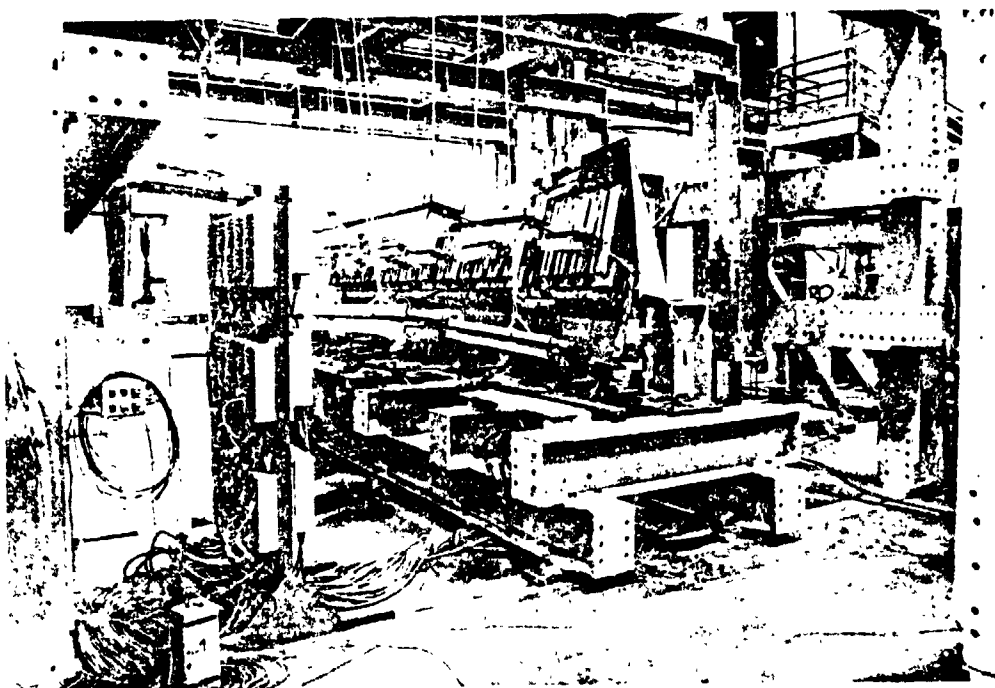


Figure 2-8. Elevator Ground-Test Setup

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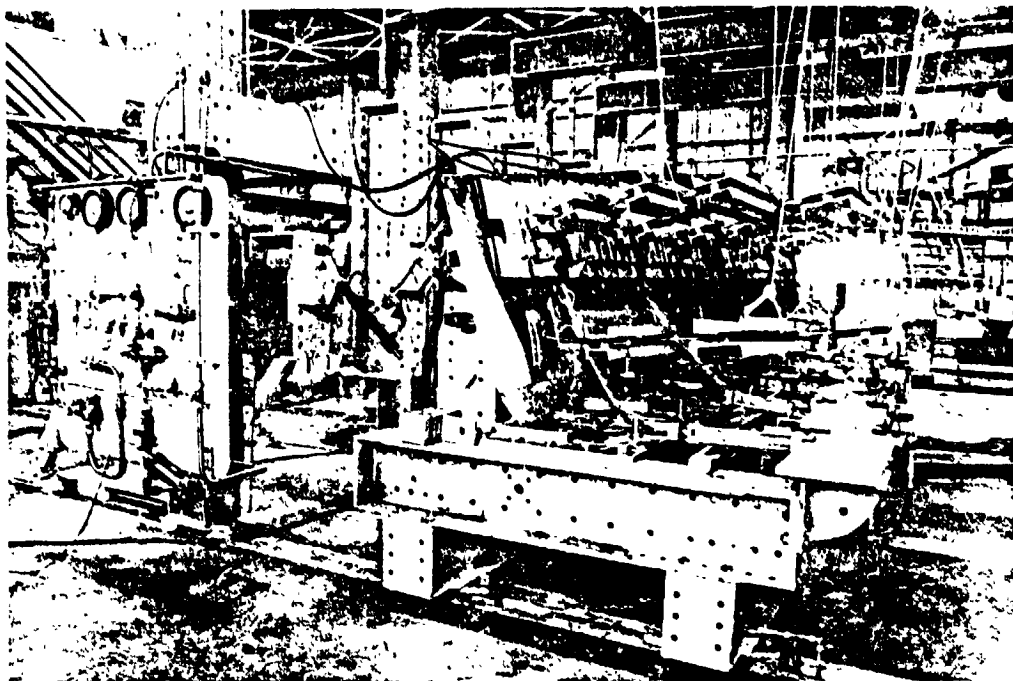


Figure 2-9. Elevator Ground-Test Setup

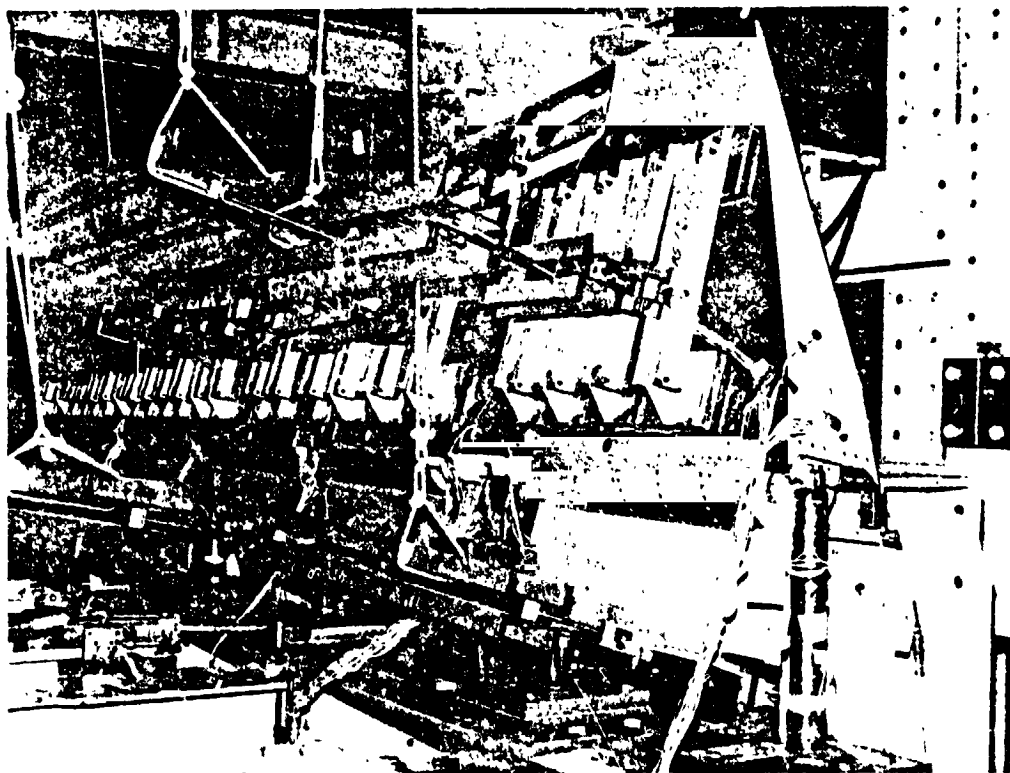


Figure 2-10. Elevator Ground-Test Setup

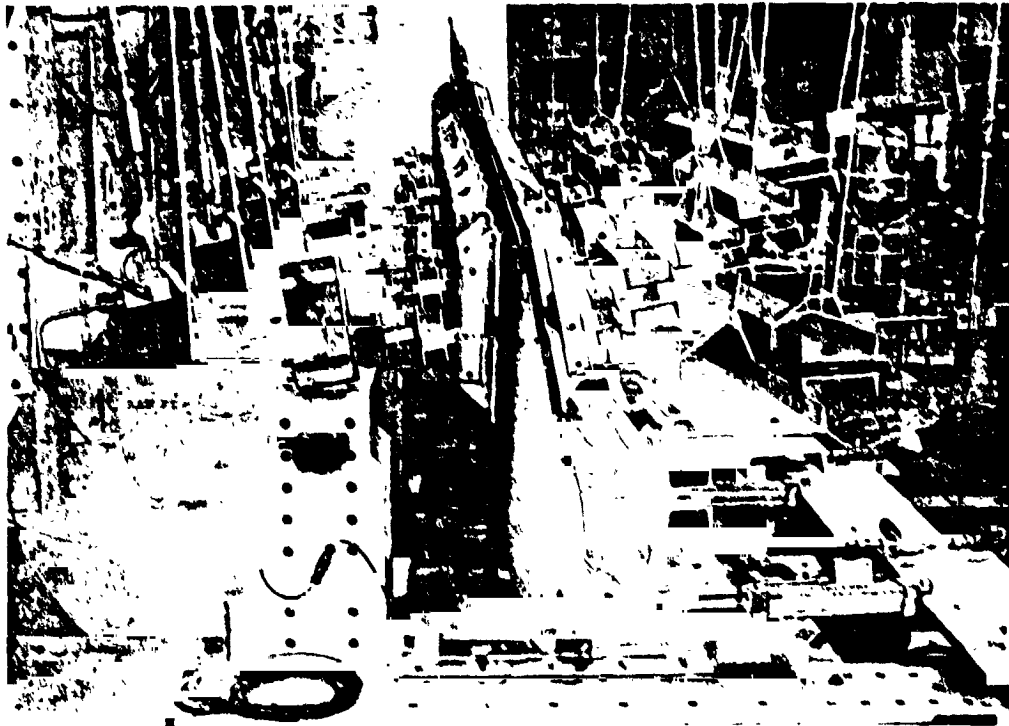


Figure 2-11. Elevator Ground-Test Setup

The test elevator is supported in a vertical position (trailing edge up) by steel pedestals at each hinge fitting, as shown in Figure 2-7. The pedestals have been calibrated with strain gages, so that fore and aft loads in the stabilizer chord plane and loads normal to the stabilizer chord plane can be determined at each hinge. The elevator hinge moment is reacted by a simulated actuator rod and reaction link that have been calibrated with strain gages to read load directly.

Pedestal bases at the inboard end hinge and the four outboard hinges can be moved in a plane normal to the stabilizer chord plane by hydraulic jacks to duplicate the bending induced by the stabilizer. The pedestal bases of the two hinges on the actuator support fitting and the support for the actuator rod and reaction link are held immobile, and are used as a datum reference for deflection of the other five hinge points.

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The applied critical limit load (load case 128) is a positive maneuver at dive speed. Two-thirds of the elevator airload was applied as a tension load to the lower surface, and one-third as a compression load to the upper surface. The portion of the balance panel loads reacted by the elevator, and the elevator nose airloads (foreward of the elevator hinge line) are applied as uniform running loads along each of the five balance panel aft hinge lines.

The pad load location and pad load distributions were optimized to match the following elevator loads and deflections for each load case tested: 1) the vertical shear along the elevator, 2) the hinge moment along the elevator, 3) skin panel out-of-plane moment along the front spar, and 4) the maximum skin panel normal deflection.

Strain gages consisting of 115 rosettes and 16 axials were installed to measure strains at critical areas, and determine internal load distributions.

Structural deflections were measured at 26 locations by electronic deflection indicators (EDI) and dial indicators. Feedback from the EDI's at each elevator hinge location was used by a computer to control the hinge pedestal hydraulic jack movement to position each hinge to the predetermined induced deflection from the stabilizer.

Thirteen hydraulic jacks were used to apply the tension and compression pad loads, the balance panel loads, and the moveable elevator hinge pedestal loads. A load cell was installed in series with each hydraulic jack to measure its applied load.

After completion of the limit load strain survey portion of the full-scale ground-test program, a repeated load (fatigue) test was begun. Testing to critical design ultimate load, damage tolerance testing, and, finally, destruction testing will follow in sequence after completion of the repeated load test.

2.4 FLIGHT TEST (Flight-test portion of program was Boeing funded)

Flight testing of the advanced composites elevator, including the ground vibration testing, has been successfully completed. The advanced composites elevator meets FAA flutter requirements, and flutter certification has been obtained.

During the ground vibration testing, portable vibration shakers were used to excite the elevator, with the horizontal stabilizer in the neutral positions. Tests were conducted with hydraulic power on and off, and with the right-hand and left-hand elevator excitation in phase and out of phase.

Accelerometers located on both right- and left-hand stabilizers, elevator, tabs, and the control column were used to measure control system natural frequencies, mode shapes, and damping characteristics. The measured natural frequencies of the advanced composites elevators were in close agreement with those used in the flutter analysis.

Flight flutter tests were conducted at several air speeds and altitudes. Measured displacement and rotation of the fin, rudder, stabilizer, and elevator--due to sharp control inputs from the elevator and rudder--were used to evaluate the natural frequency and damping characteristics of the empennage with graphite/epoxy elevators.

Measured data from the engineering and certification flight tests of both the production aluminum elevators and the advanced composites elevators will be compared, to verify that the stability and control, and autopilot characteristics of a 727 equipped with advanced composites elevators are the same as for the baseline airplane with production aluminum elevators. Submittal of data to obtain FAA certification for stability and control, and autopilot characteristics will be accomplished upon completion of the analysis of measured flight data.

The advanced composites elevator flight-test airplane was flown by an FAA pilot, as part of the stability and control and autopilot certification flight testing. The advanced composites elevator will remain installed on the Boeing 727 flight test airplane for an unspecified time.

2.5 DESIGN

Project is continuing to perform design-sustaining activity. The majority of the work is not involved in changing part-configuration, but in providing drawing interpretation and clarification. It is correcting drawing errors and inconsistencies, and incorporating manufacturing requests to simplify fabrication of parts.

One drawing error requiring a change in design involved the control tab bob weight (65C17541). The drawing required use of a heavy potting compound, which resulted in an improper center of gravity location. Furthermore, experience in fabricating control tabs indicated that the availability of two bob weight configurations would facilitate balancing the tab. For these reasons, the drawing was revised to use a lighter potting compound, and a lead disk was added to create another weight configuration 0.10 kg (0.22 lb) heavier than the original bob weight.

Another design change resulting from production experience occurred in the graphite/epoxy layup of the control tab bonded assembly (65C17505-3 and 65C17505-20). Use of cocured skin plies on the tab graphite/epoxy sandwich assembly resulted in a warp up to 4.06 mm (0.16 in) high along the trailing edge. This assembly is made in a three-stage bonding process that is shown in Figure 2-12. The tab drawing has been changed to allow use of precured skins in stages 2 and 3 of the bonding process. Experience shows the tab assemblies that use a precured upper skin have a warp less than 1.27 mm (0.050 in) high along the trailing edge. This is an acceptable resolution of the concern.

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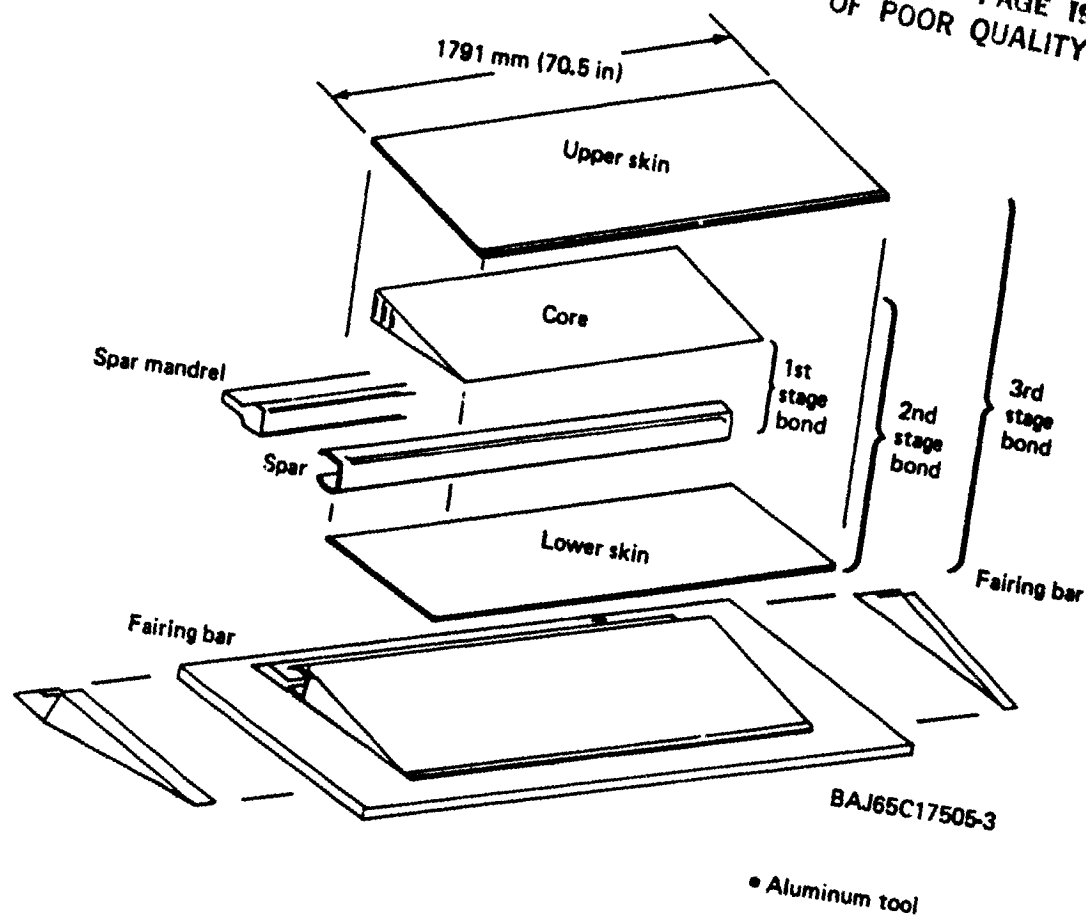


Figure 2-12. 727 Control Tab

2.6 WEIGHT STATUS

The addition of actual graphite/epoxy and metal detail parts weights to the predicted weight status results in a weight reduction of 2.0 kg (4.4 lb) from the previously published weight. The current predicted elevator system weight of 189.3 kg (417.4 lb) is detailed in Table 2-3. The 26% weight reduction remains unchanged.

The first two elevator system shipsets have been weighed. Actual versus predicted weights are shown in Table 2-4.

Table 2-3. Weight Status—Seventh Quarterly Report

Item	① Aluminum baseline, kg (lb)/ airplane	② Advanced composites system weights		③ Current report, kg(lb)/ airplane	④ Δ previous to current, kg(lb)/ airplane ③ - ②	⑤ Weight difference, kg(lb)/ airplane ③ - ①	⑥ Weight difference, $\frac{⑤}{①} \times 100$
		Previous report, kg (lb) airplane					
Front and rear spars	35.2 (77.7)	27.9 (61.5)		28.4 (62.7)	+0.5 (+1.2)	-6.8 (-15.0)	-19
Inspar ribs	12.0 (26.6)	6.6 (14.6)		4.4 (9.6)	-2.2 (-5.0)	-7.6 (-17.0)	-64
Skin panels	52.8 (116.3)	44.6 (98.3)		45.3 (99.8)	+0.7 (+1.5)	-7.5 (-16.5)	-14
Control tab	11.1 (24.4)	6.3 (13.8)		6.8 (15.0)	+0.5 (+1.2)	-4.3 (-9.4)	-39
Horn ribs and fairings	6.0 (13.2)	3.6 (8.0)		3.8 (8.4)	+0.2 (+0.4)	-2.2 (-4.8)	-36
Corrosion protection	0 (0)	0.6 (1.3)		0.6 (1.3)	0 (0)	+0.6 (+1.3)	-
Lightning protection	0 (0)	1.2 (2.7)		0 (0)	-1.2 (-2.7)	0 (0)	-
Replaced structure	117.1 (258.2)	90.8 (200.2)		89.3 (196.8)	(-1.5) (-3.4)	-27.8 (-61.4)	-24
Balance panel weights	32.0 (70.6)	0 (0)		0 (0)	0 (0)	-32.0 (-70.6)	-100
Balance panel hinges	54.6 (120.3)	38.3 (84.6)		38.3 (84.4)	0 (-0.2)	-16.3 (-35.9)	-30
Horn balance weight	18.8 (41.5)	23.6 (52.0)		23.6 (52.1)	0 (+0.1)	+4.8 (+10.6)	+26
Elevator adjust weights	0 (0)	2.3 (5.0)		1.8 (4.0)	-0.5 (-1.0)	+1.8 (+4.0)	-
Nose ribs and skins	8.9 (19.6)	20.1 (44.3)		20.1 (44.4)	0 (+0.1)	+1.2 (+2.8)	+7
Balance panel structure	16.0 (35.2)	16.2 (35.7)		16.2 (35.7)	0 (0)	+0.2 (+0.5)	+1
Revised structure	140.3 (309.2)	100.5 (221.6)		100.0 (220.6)	(-0.5) (-1.0)	-40.3 (-88.6)	-29
Total elevator system weight/airplane	257.4 (567.4)	191.3 (421.8)		189.3 (417.4)	(-2.0) (-4.4)	-68.1 (-150.0)	-26

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Table 2-4. Actual Versus Predicted Weights

Component	Predicted, kg (lb)		No. 1 shipset, kg (lb)		No. 2 shipset, kg (lb)	
Left-hand and right-hand elevator surface	153.4	(338.2)	152.8	(336.9)	153.5	(338.5)
Left-hand and right-hand tab assembly	6.8	(15.0)	6.8	(14.9)	6.9	(15.2)
Left-hand and right-hand balance panels	29.1	(64.2)	29.0	(64.0)	29.0	(63.9)
Total elevator system/airplane	189.3	(417.4)	188.6	(415.8)	189.4	(417.6)

SECTION 3.0

PRODUCTION

3.1 ADVANCED COMPOSITES COMPONENTS

Three and one-half shipsets of advanced composites components have now been fabricated for the model 727 elevator program, with shipsets two and three being completed during the past quarter. No significant layup, cure, or final part configuration difficulties were encountered other than those, as reported in the sixth quarterly, that occurred during fabrication of the first one-half shipset. A shipset of advanced composites components involves 72 end-item part numbers, but the total quantity required is 160, due to multiple use of some parts. Contract requirements will be completed during the next quarter.

3.2 ASSEMBLY PROGRESS

The first full shipset of assemblies was completed per schedule December 12, 1978, and the second February 2, 1979. Assembly work was accomplished with fewer problems than on the first left-hand test unit.

Fiber breakout during drilling and countersinking operations was minimal. The last report indicated that diamond-coated cutters were being considered for countersinking, but this idea has been rejected because the cutters produced small ridges in the countersink. Also, it was determined that proper operator techniques, using three fluted cutters with carbide inserts and plastic pads on the microstop foot, would produce acceptable countersinks. An alternative method for drilling through advanced composites/metal stackups was instituted to prevent fiber breakout caused by metal chips backing up the drill flutes of full-size carbide drills. Die drills had been considered, but it was found that using a No. 40 pilot drill, followed by reaming with a solid carbide high-speed taper

drill, offered a better solution. It has also been determined that the application of primer paint on the external surfaces of the skin panels, as was done on the No. 1 and No. 2 shipsets of panels, essentially eliminated, fiber breakout.

Fastener revisions were implemented on the second shipset in an effort to resolve certain assembly problems. These are discussed below:

3.2.1 Hi-Lok Replacements

Titanium Hi-Lok bolts with CRES collars were being used throughout the rear spar, lower skin, and actuator rib areas. The installation procedure was found to be difficult. Design restrictions limit the access to the collar with standard tools. Modified tools afforded little relief. Certain installations in the rear spar assembly were taking as long as 2 hr. In addition, the combination of titanium and CRES resulted in higher torque required to break the collars.

Hi-torque, single-slot bolts replaced the Hi-Loks to allow driving from the outside, and JC nuts replaced the CRES collars to meet the maximum torque specifications. It was found, however, that the hi-torque head was difficult to grip, and it easily "cammed out". (Torque resistance between the bolt and collar exceeded the design capability of the slot in the bolt head.)

To correct the problems inherent with the hi-torque bolts, a new bolt, the "torque-set", was used on the elevator (see Figure 3-1). This bolt has an offset phillips head configuration with excellent grip. Torque-set bolts replaced hi-torques on the lower skin and rear spar on the second shipset. It has been estimated that an 8-hr improvement has been realized on the rear spar alone.

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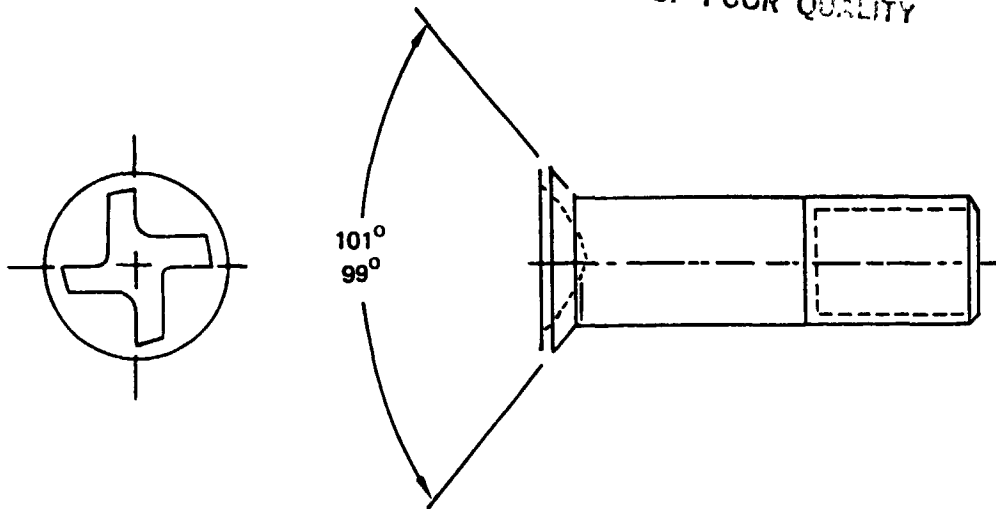


Figure 3-1. Bolt, 100° Flush Reduced Head

3.2.2 Nutplate Replacements

Nutplates used in the upper skin closeout were found to be very time-consuming in installation. The upper skin is a permanent installation, and the bolts do not need to be removable. Blind fasteners, therefore, were used in this area. The "visu-lok" blind is being used in conjunction with a stainless steel washer that must be bonded to the back side of the graphite/epoxy. The bonding process is considered an interim step, in that washerless systems are under development. Even with the time involved in bonding the washers in place, the overall installation time for the panel was considerably reduced (see Figure 3-2).

3.3 ASSEMBLY PROGRESS--FIVE SHIPSET FOLLOW-ON

Assembly of the third shipset of elevators began February 5, 1979, and is progressing per schedule toward a March 30, 1979 completion date.

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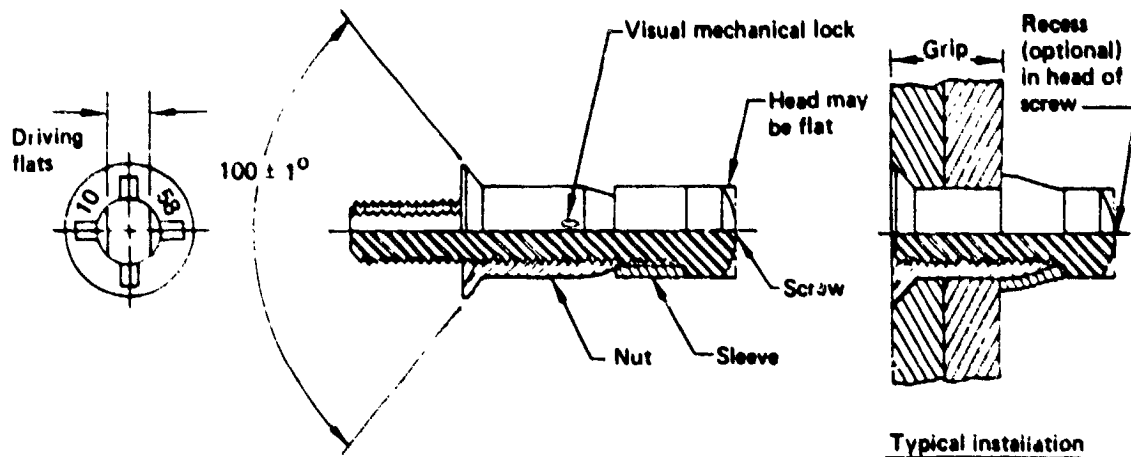


Figure 3-2. Visu-lok, Fastener, Blind—Internally Threaded, External Sleeve Titanium—Reduced Flush Head, Self-Locking, 75 ksi Shear